Contingency Constrained Optimal Meter Placement for Power System Observability using Biogeography Based Optimization

K.Jamuna, Member, IACSIT and K.S.Swarup, Senior Member, IEEE

Abstract— The paper presents a biography based optimization algorithm to design the measurement configuration which makes the power system network observable. The optimal meter locations are obtained under normal as well as contingency cases. The normal operation of the power system means that the equality and inequality constrains of power system should be met. The optimal and reliable meter locations are identified against two types of contingencies named as single measurements loss and single branch outages by modifying the fitness function derived in normal conditions. The effectiveness of the proposed approach is demonstrated using IEEE standard systems.

***Index Terms*— Biogeography Based Optimization; Meter Placement, Network Observability; State Estimation**

I. INTRODUCTION

The power system structure and operations are become more complex due to ever increase in power demand. The power system monitoring, operation and control of today's large scale power system with interconnections, deregulation, reliability and security pose demanding computational issues. State Estimators (SE) have been widely used as a vital tool for on-line monitoring, analysis and control of power systems. Entire power system measurements are obtained through RTU (Remote Terminal Unit) of Supervisory Control and Data Acquisition (SCADA) systems which have both analog and logic measurements. SE uses a set of these measurements and it cannot be solved unless the system is fully observable. Therefore the measurement placement becomes a significant problem in SE, which requires sufficient measurements to make the system observable.

Network observability analysis is determined whether the state vector of a whole system is able to calculate with available number and location of measurements. If so, the network is said to be observable, otherwise it is unobservable. Optimal Meter Placement (OMP) of state estimation for maintaining observability has been proposed by many researchers. In order to reduce the metering cost, meters are to be placed only at the essential location in the system. The meter placement problem was first proposed in [1], which minimize the variance of estimated quantities. The same problem was addressed based on measurement reliability by Ariatti [2]. Baran proposed a meter placement method for minimizing the meter cost based on state estimation accuracy [3]. Observability analysis can be solved by topological [4-6], numerical [7-8] and algebraic methods [9]. A maximal forest of full rank for a measured network is found in the topological observability algorithm. If the maximal forest of full rank is a spanning tree, then the network is topologically observable. Numerical observability algorithm is based on numerical determination of gain matrix. The network is observable, when the gain matrix is non singular and the rank is N, where N is the number of buses in the power system network. Bei Gou and Ali abur have contributed an algorithm for meter placement using numerical observability [10-11]. In addition to the observability, bad data measurements have been done in [12]. Optimal meter placement during contingencies is also presented in [13]. The numerical observability method is complicated which requires iterative algorithms. [9] explained algebraic observability where bus injection and line currents are considered as measurements. Heuristic methods are also contributed for optimal meter placement with and without contingencies. Simulated annealing, Genetic algorithm and Tabu search are used for obtaining optimal location of meters in [14], [6] and [15, 16] respectively. The complete survey of meter placement for power system state estimation is enlightened in [17].

A new concept based on biography has been proposed by Dan Simon [18]. The biography based optimization (BBO) technique has been used in sensor selection for aircraft engine health estimation [18] and economic dispatch in power systems [19]. In this work, BBO is used to achieve the optimal meter placement under normal and contingency conditions.

The paper is structured as follows: in Section II, the problem of meter placement under both normal and contingency cases is described. BBO optimization technique is presented in detail in section III. Section IV explains the BBO technique for optimal meter placement. Simulation results and Conclusions are given in section V and VI.

II. METER PLACEMENT PROBLEM

The decoupled linear measurement model used in power system state estimation is represented by

$$Z = HX + \varepsilon \tag{1}$$

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K.Jamuna is with the Indian Institute of Technology, Madras, Chennai, India -600 036 (corresponding author to provide phone: +91-44-2257 5461; fax: +91-44-2257 4402; e-mail: jamunakamaraj@gmail.com).
K.S.Swarup is with the Indian Institute of Technology, Madras, Electrical Engineering Department, Chennai, India – 600 036 (e-mail: swarup@ee.iitm.ac.in).

Where

Z - Measurement vector formed by voltage magnitude, real power flow and power injection

H - Measurement Jacobian matrix ($\frac{\partial h(X)}{\partial X}$

h(X) - Non linear function relating the measurements to the system states

X – System state Variables (|V|, δ)

ε - Noise in measurements

The power system states are estimated using Weighted Least Square (WLS) method. The estimator equation is given in eqn. (2).

$$\hat{X} = (H^T R^{-1} H)^{-1} (HR^{-1} Z) \quad (2)$$

A unique solution is obtained when gain matrix G= ($H^T R^{-1} H$) is non singular or H has full rank (2N-1). State estimation cannot be solved unless the system is fully observable. A network is said to be observable when H matrix is full rank. The measurements which make the system observable are known as essential measurements.

The linearized models of the power system are decoupled into (Pδ) and (QV) measurement model. Usually P, Q measurements are received as pairs in control centers, so observability analysis can be separately used like (Pδ) and (QV). The observability algorithms are sufficient to verify any one of the Pδ or QV decoupled measurement model. These decoupled models can be written as follows.

$$Z_{p\delta} = H_{p\delta}\delta + \sigma_1 \quad (3)$$

$$Z_{QV} = H_{QV}V + \sigma_2 \quad (4)$$

Where

$Z_{p\delta}$ - Real power measurement vector

Z_{QV} - Reactive power measurement vector

$H_{p\delta}$ - Real power measurement Jacobian $\frac{\partial h_{p\delta}}{\partial \delta}$

H_{QV} - Reactive power measurement Jacobian $\frac{\partial h_{QV}}{\partial V}$

σ_1, σ_2 - Noise in real and reactive measurements respectively

In this paper, Pδ decoupled linear measurement model is used for observability analysis. The measurements which make the system observable are known as essential measurements. The elements of the H matrix are not affected by the operating point, but depend on measurement configuration. It is enough to evaluate H as flat start. Note that the measurement matrix should be linearly independent to minimize the number of measuring devices in the power system networks.

The main objective of Optimal Meter Placement (OMP) is minimizing the installation cost of measurement placement. The installation cost is directly depends on the number of measurements. The objective function for topological observability may be written as follows.

Under Normal Conditions [20]

$$\min : \sum_{i=1}^{m} meters \quad (2)$$

$$\text{S.T } Rank(H_{p\delta}) = N - 1 \quad (3)$$

Under Contingency Conditions

$$\min : \sum_{i=1}^{m} meters \quad (4)$$

$$\text{S.T } Rank(H_{p\delta}) = N - 1 + k \quad (5)$$

Where,

m - No of measurements

N - Number of buses in the power system network

k - No of measurements lost / Outaged branches

The normal condition of the power system is defined as the power generation of the network met the power demand without violating any operational constraints. If there is any outage of transmission line / loss of measurements, then power system go to insecure state which is named as contingency.

Reliable measurement configurations are designed under contingency conditions in such a way that the rank of H matrix should be full after each and every measurement loss or by the removal of any one of the branch at a time.

III. Biogeography Based Optimization

Biography is the study of distribution of species in nature and it is analogous to general problem solutions. The problem can be of any area in life (Engineering, Economics, Medicine, Business, Urban Planning, Sports, etc) as long as we have qualitative measure of the suitability of a given solution. An island is a locality of group of species living together. Each island is geographically isolated from the other one. The more generic term of an island is Habitat. The habitat features or characteristics habitability are called Suitability Index Variables (SIV). They are rainfall, temperature, diversity of vegetarian, land area etc. Each habitat has a set of SIVs and the goodness of this habitat is called as Habitat Suitability Index (HSI). Here, SIVs are the independent variables and HSI are dependent variable. In Genetic Algorithm (GA) terminology, the habitat and HSI are equivalent to the population and fitness value respectively. The mathematical model of the biography explains how the new species arise or extinct within those habitats. The BBO algorithm is developed based on the mathematics of biogeography.

In BBO, a habitat T is a vector of R (SIV) real integers initialized randomly and HSI of each habitat is evaluated. The number of habitats is assumed as P and each one has R characteristics. The individual character of a habitat is represented by SIV_k, where k= 1 to R. The depiction of the habitat matrix is shown in Fig. 1.

$$T = \begin{array}{c} 1 \\ 2 \\ 3 \\ \\ \\ P \end{array} \begin{bmatrix} SIV_1 & SIV_2 & SIV_3 & . & . & . & SIV_R \\ SIV_1 & SIV_2 & SIV_3 & . & . & . & SIV_R \\ SIV_1 & SIV_2 & SIV_3 & . & . & . & SIV_R \\ . & . & . & & & & \\ . & . & . & & & & \\ SIV_1 & SIV_2 & SIV_3 & . & . & . & SIV_R \end{bmatrix}$$

Fig.1 Depiction of the Habitats and its SIVs

The BBO algorithm works based on two mechanisms named as migration and mutation. In migration, the information is shared between habitats that depends on emigration rates (μ) and immigration rates (λ) of each habitat. The habitats are modified depending on habitat modification probability P_{mod} that is user defined parameter. Each habitat has its own λ and μ, which are functions of the number of species in the habitat. A good solution is analogous to an island with high HSI and poor solution represents an island with a low HSI. High HSI individual resist the changes happened in that habitat than the low HSI individual. Poor solutions accept more useful information from good solution, which improve the exploitation ability of algorithm.

Habitat modification (Migration) algorithm is described as follows [18].

```
Select Hi Having probability λi
if Hi is selected then
   for j=1 to P do
   Hj having probability μi
      if Hj is selected then
      Randomly select a SIV γ from Hj
      Replace a random SIV in Hi with γ.
      end if
   end for
```

The selection of habitat to be modified is chosen using habitat modification probability. In that habitat, its immigration rate λ is used to probabilistically decide whether to modify each SIV's or not. Another habitat is selected based on emigration rate μ, its SIV will migrate randomly to the selected habitat's SIV.

The migration is similar to the Global Recombination Approach (GRA) of Evolutionary Strategies and GA. The migration is an adaptive process, which changes the existing habitat and improves the habitat characteristics. But GRA is a reproductive process and produces a new population.

In BBO, the mutation is used to increase the diversity of the population to get the good solutions. The low and high HSI valued habitats have less possibility to mutate, which gives them to a chance of improving even more than they have. But average HSI valued habitats have more possibility to mutate that is hopefully improving already.

Mutation operator modifies a habitat's SIV randomly based on mutation rate m. Mutation rate of each habitat is calculated by species count probabilities. The probability of each species depends upon the immigration and emigration rate of the habitat and is calculated with the following differential equations.

$$\dot{P}_S = (-\lambda_S + \mu_S)P_S + \mu_{S+1}P_{S+1} \quad \text{When } S=0 \quad (6)$$

$$\dot{P}_S = (-\lambda_S + \mu_S)P_S + \mu_{S-1}P_{S-1} + \mu_{S+1}P_{S+1} \quad \text{When } 1 \le S \le P_{S_{\max}} \quad (7)$$

$$\dot{P}_S = (-\lambda_S + \mu_S)P_S + \mu_{S-1}P_{S-1} \quad \text{When } S = S_{\max} \quad (8)$$

The species count in the habitat changes from time to time. λ_S, λ_{S-1}, λ_{S+1} and μ_S, μ_{S-1}, μ_{S+1} are the emigration and immigration rate of the habitat having S, S-1 and S+1 species respectively. P_S, P_{S-1} and P_{S+1} are the species count probability of habitat with S, S-1 and S+1 species respectively. S_{max} is the maximum species count in the habitat.

The mutation rate m is expressed as

$$m(s) = M_{\max} * \left(1 - \frac{P_s}{P_{\max}}\right) \quad (9)$$

where $M_{\max}$ is a user defined parameter and P_{max} = argmax(P_s), S=1, 2,.....P. P is number of Habitat/Island, P_S is probability of Habitat S.

The selected habitat is mutated with the randomly generated real variable in the concerned location of SIVs. This mutation process is similar to the mutation scheme used in the GA.

Habitat mutation is described as follows.

```
for j=1 to R do
Use λi and μi to compute the probability pi
Select SIV Hi(j) having probability pi.
      if Hi(j) is selected then
      Replace Hi(j) with randomly generated SIV.
      end if
end for
```

IV. Implementation of BBO to Optimal Meter Placement

Observability relies on location, type of the measurements and system topology. The network topology may change due to daily switching operation. It is necessary to design the appropriate measurements to maintain the observability. Rank deficiency will occur due to loss of essential measurements or change in the system configuration like branch outage.

a) Representation of the Habitat: In this problem, the habitats are represented by vectors and carry the binary values. The habitat vector length is equal to the addition of number of nodes and branches in the power system. The nodes and branches are corresponds to the power injections and power flows respectively. The value is equal to 1; the power injection/power flow meters are present in that node/ branch. Otherwise its value is 0.

b) Initialization: The actual BBO vectors are initialized by real numbers. In this problem, binary variables are used for the representation of meter placement which can be named as binary BBO.

c) Fitness Evaluation: In order to meet the observability criteria, the essential measurements are obtained under normal operation of the power system. The essential measurements are the set of measurements which makes the system to be fully observable. The Optimal Measurement Placement (OMP) has been done using hybrid Genetic and Simulated annealing in [21]. In this paper, BBO is used for the selection of optimal measurements. The fitness function of this problem under normal conditions is defined by eqn. (10).

$$J = \frac{1}{1 + |N - 1 - CM| + (N - 1 - Rank(H_{p\delta}))} \quad (10)$$

For single measurement loss and single line outage contingencies, the extra one measurement is needed to add with the essential measurement sets. Thus the fitness function against contingencies is as shown in eqn. (11).

$$J = \frac{1}{1 + |N - 1 - CM| + (N - 1 - Rank(H_{p\delta})) + Penalities} \quad (11)$$

Penalties= Penality1+Penality2

The penalties are defined as follows

Penalty1 =
- **S1**- if SIV has number of measurements equal to N and Rank ($H_{p\delta}$) =N-1 where S1ϵ (0, 1, 2…N) is the number of measurements removed one by one and makes the system observable.
- N – Otherwise

Penalty2 =
- **S2**- if Penalty1 = 0 where equal to N and Rank ($H_{p\delta}$) =N-1 where S2ϵ (0, 1, 2…N_L) is the number of branches is removed one by one and makes the system observable.
- N_L - Otherwise

J and CM in eqn. (10) and eqn. (11) are the fitness value and the number of measurements in power system network. The S1 and S2 are added to the eqn. (11) for single measurement loss and single branch outage respectively. If these values are zero the system is observable under contingencies. The best fitness value of the placement problem is equal to one.

d) BBO operators: The changes in the existing habitats are done in two steps of this algorithm: Migration and Mutation.

Migration: The immigration and emigration rates of each habitat are estimated based on HSI value. In the original BBO, these rates have linear relationship with the number of species in the habitat. Based on the problem, the relationship between the species and rates can be assumed as non-linear. In this paper, the number of species is replaced by the number of meters in the system. The emigration rates are increased linearly with the number of meters and vice versa for immigration rates. Based on the P_{mod}, λ and μ, the non elite habitats are modified.

Mutation: The mutation is the process to avoid the premature convergence. The single character or multiple characters of a habitat can be changed by flipping SIV's in the existing habitats and it produces a new-fangled habitat. In this paper, standard mutation is used with the mutation probability (M_{max}). But the different mutation operators used for GA can also be applied in this algorithm.

e) Keep Elitism: The elite habitats are kept for the next generation, which is chosen based on HSI. The number of elite habitats depends on the elite parameters.

f) Avoid Duplicates: Replace the worst habitats with the Elite habitats. Avoid duplicate habitats for next generation.

g) Convergence criteria: The algorithm will stop when the best HSI value is equal to 1 or maximum generation is reached.

The BBO algorithms for optimizing the measurements are described as follows.

1. Read the system topology.
2. Specify habitat size, habitat modification probability, Immigration probability bounds per gene, and maximum immigration and migration rates of each island and mutation probability.
3. The habitats are randomly initialized.
4. Evaluate HSI of each habitat.
5. If G < maximum generation and best fit ≠ 1, otherwise go to step 13.
6. Sort habitats based on its HSI. Keep the best HSI habitats (Elite HSI) and corresponding habitat (Elite Habitat) for the next generation.
7. For each habitat, map the immigration rate λ and emigration rate μ.
8. Probabilistically use λ and μ to modify each non elite habitat
9. Perform the mutation
10. Evaluate the fitness of each new habitat and sort
11. Replace the worst habitats with the Elite habitats
12. Set G=G+1, return to step 5.
13. Store the best Habitat

V. Simulation Results

Figures the optimal location of SCADA measurements for power system state estimation has been identified under normal and contingencies using heuristic optimization tool (BBO). The single line outage and single measurement loss will be considered as contingencies. It has been tested on 10 bus test system, IEEE 30 and 57 bus systems. The simulations are carried out in MATLAB environment on an Intel Pentium IV (2.8GHz) with 1.25GB RAM.

The following BBO parameters have been used after number of careful experimentation: habitat size=20; habitat modification probability=1, Immigration probability bounds per gene = {0, 1}, step size for numerical integration of probabilities =1, maximum immigration and migration rates of each island = 1 and mutation probability =0.005.

The Performance analysis of Measurement Placement is shown in Table I. The proposed work is compared with Hybrid Genetic algorithm - Simulated annealing (HGS) method based work done in [21]. Table I shows that the computation time of BBO algorithm for optimal meter placement under normal operation of power system. Even the worst CPU time for obtaining the required meters are also less than the HGS method. The BBO algorithm works faster than HGS algorithm.

TABLE I. PERFORMANCE ANALYSIS OF MEASUREMENT PLACEMENT UNDER NORMAL OPERATION

Test Case	Algorithm	CPU time, s		
		Best	Worst	Average
10 bus	BBO	0.02	0.4	0.23
	HGS	0.06	1.2	0.42
IEEE 14	BBO	0.072	0.3	0.23
	HGS	0.38	1.92	1.09
IEEE 30	BBO	0.97	3.58	1.49
	HGS	1.47	7.44	3.92
IEEE 57	BBO	5.87	8.65	7.15
	HGS	6.89	14.31	9.52

Fig. 1 shows the change of fitness function value or HSI values of BBO applied to various test cases. All test cases are reached to the best fit=1, but the number of generations taken for reaching best fitness is increased linearly with the system nodes. Similarly, the elite parameters are assumed to be increased linearly with the system nodes.

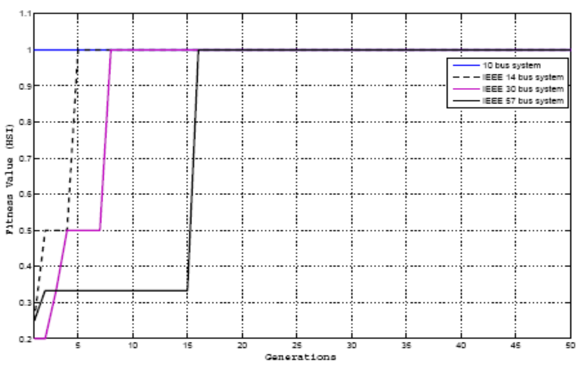

Figure 1. BBO results of HSI for Standard Test Cases

The elite parameters have the effect on the solution converge of the test cases, which is shown in Fig. 2 for 30 bus system. When the elite parameters are high or low, the computation time will be more. For this system, the optimal elitism is 15, while the habitat size is 100.

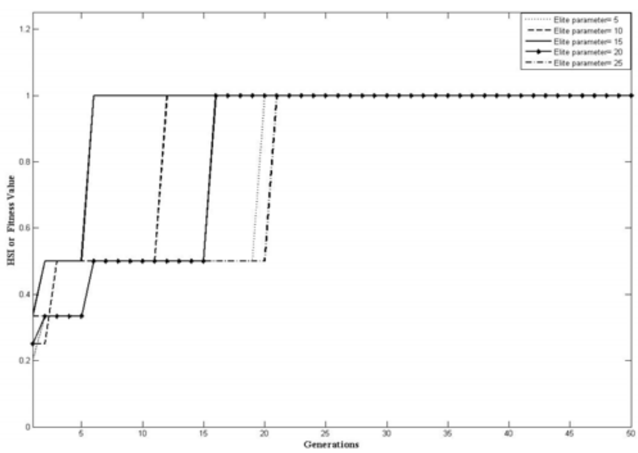

Figure 2. The effect of elitism on convergence for IEEE 30 bus systems

The network diagram of 10 bus system is shown in Fig. 3. There are 5 Power Injections (PI) and 4 Power Flows (PF) are presented under normal operations, which make the system to be observable. By visualization of the meter assignment, the PF has a unique assignment to the measured branch, while PI is assigned to any one of the incident branches. Either bus 2 or bus 5 is observable by the PF meter to be placed in the branch 2-5 which is shown in the Fig. 3. By the placement of PI meter at bus 2, any one of the bus (1, 2, 3 and 5) are observable. The other buses can be viewed in the similar fashion.

The comparison between HGS and BBO algorithm in terms of computation time are shown in Table II under single measurement loss and against both single measurement loss and branch outage. BBO gives faster solution with less number of population/habitat. The resultant measurement sets of each test case are tabulated in Table III. The numbers of measurements are increased by one when the contingency occurs. Under normal operation 10 bus test cases need only 9 measurements which are shown in Fig. 3.

TABLE II. PERFORMANCE ANALYSIS OF MEASUREMENT PLACEMENT AGAINST CONTINGENCIES

Test Case	Algorithm	Best CPU time, s			
		Habitat Size	One Meas. only	Habitat Size	Both (Loss/outage)
10 bus	BBO	20	0.12	20	0.06
	HGS	20	0.17	20	0.41
IEEE 14	BBO	20	0.29	20	0.98
	HGS	20	1.49	30	2.69
IEEE 30	BBO	20	1.27	30	2.08
	HGS	30	9.17	40	16.00
IEEE 57	BBO	30	2.83	50	4.47
	HGS	50	16.28	200	70.78

TABLE III. OPTIMAL MEASUREMENT PLACEMENT UNDER CONTINGENCIES OF TEST CASE

Test Case	PI[a] Measurements	PF[b] Measurements
10 bus	1,2,4,6,7,9,10	6,7,12
IEEE 14	3,7,8,13	1,4,5,7,8,10,12,13,14,16
IEEE 30	3,4,5,6,9,11,12,14,19,20,21 22,24,26,28	1,3,7,8,10,11,13,16,19,20,21 26,30,31,37
IEEE 57	5,8,9,13,15,17,18,20,21,24, 27,28,30,32,37,38,39,40,42 43,48,51,53,54,56	2,3,8,9,19,21,23,24,26,27,28 30,33,37,38,42,43,44,45,47, 53,54,59,61,63,64,67,68,72, 74,76,80

a. PI – Power Injection b. PF- Power Flow

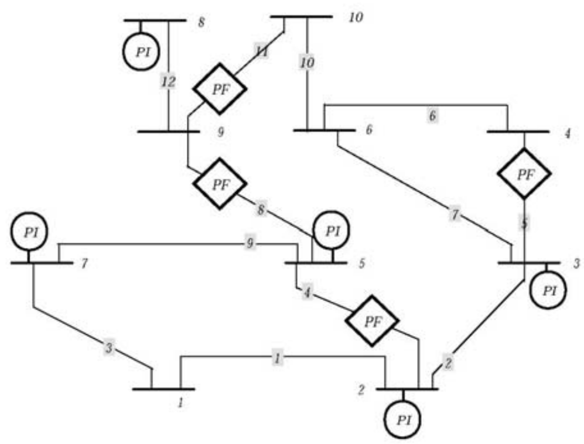

Figure 3. Measurement Configuration for 10 bus sytem under normal operation

The optimal meter configurations for IEEE 14 bus power system network with contingency cases are shown in Fig. 4. It has 4 power injections and 10 power flows. Similarly the meter location for IEEE 30 bus system is represented in Fig. 5. Note that optimal solutions are not unique.

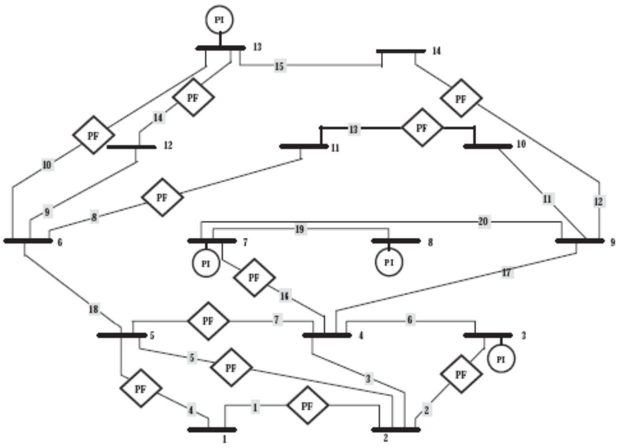

Figure 4. Optimal meter location for IEEE 14 bus sytem including both contingencies

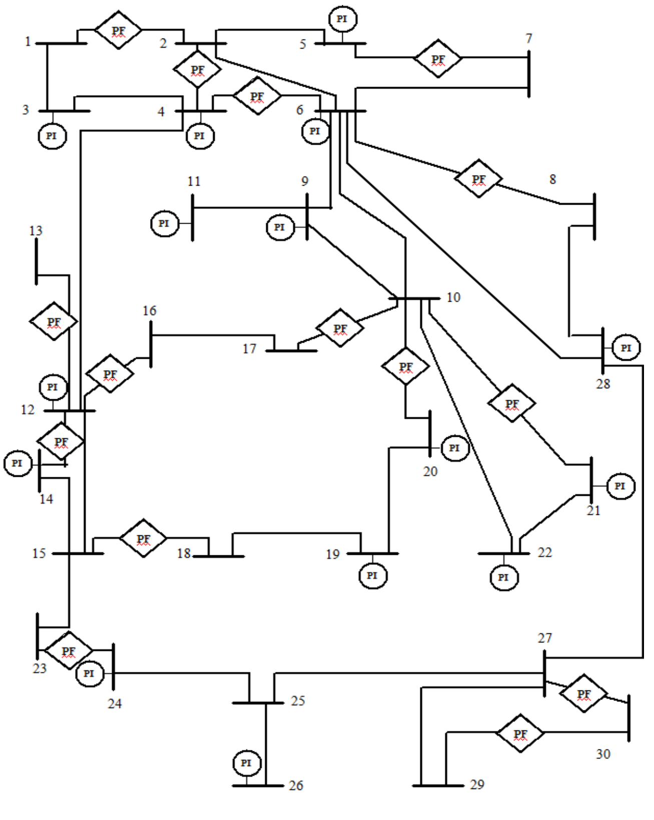

Figure5. Meter location for IEEE 30 bus sytem including both contingencies

During contingencies, the measurements are increased to 10 are depicted in 1st row of Table III. This table explains about the optimal meter locations against the contingency conditions of various test cases. The number of required meters is equal to the number of nodes in the system under the contingency cases. The system observability is maintained even the removal of any one of the meters or single branch outage with the measurements obtained through the configured meters.

VI. CONCLUSION

The paper is concerned about the optimal meter placement for making a power system topologically observable. A Biogeography Based Optimization is used to determine the optimal measurement configuration against normal and a single measurement loss or/and branch outage cases. Numerical results on IEEE test systems indicate that the proposed placement method satisfactorily provides the optimal and reliable meter location that ensures the state estimation to be solvable under normal and the given contingency conditions.

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K.Jamuna received her Bachelor's Degree in Electrical and Electronics Engineering from Thiagarajar College of Engineering, Madurai, India, Masters in Power Systems Engineering from College of Engineering Trivandrum, India and currently pursuing PhD in IIT Madras in the area of Power system. She has a working experience of about 8 years in various engineering colleges. Her research interests are power system state estimation, wide area measurement systems and control.

K.S. Swarup is currently a professor in the Department of Electrical Engineering, Indian Institute of Technology, Madras, Chennai, India. Prior to his current position, he held positions at Mitsubishi Electric Corporation, Osaka, Japan and Kitami Institute of Technology, Hokkaido, Japan, as a visiting research scientist and a visiting professor respectively during 1992 -1999. His areas of research are artificial intelligence, Knowledge based systems, and computational intelligence, soft computing and object oriented modeling and design of electrical power systems. He is a senior member of IEEE since 2003.